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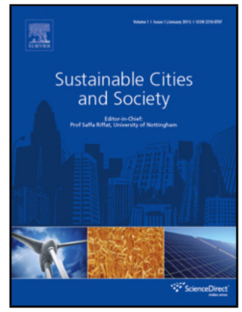

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Dissonance in Building Services Guidance: Implications for Energy Consumption

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Highlights

- Examination of building services guidance for swimming pool halls
- Modelling of the sensible and latent conditioning loads using industry standard software.
- Estimation of guidance dissonance on pool hall energy usage

Abstract
Building designers rely on a plethora of design guidance beyond compulsory building codes or regulations. However, it has been noted that guidance can be conflicting or contradictory. There is also evidence that design teams opt for ‘the safe option’, or that which colleagues have used. This is known to have led to the over-engineering of buildings and systems, potentially leading to unnecessary energy use, in direct conflict with the low carbon agenda. To quantify the potential scale of the impact, we investigated the energy use of commercial swimming pool halls, using the full-range of common design standards. Swimming pools were chosen due to their high-energy demand and because there are many guidance documents available from different sources. We found that different standards (which revolve around temperature, humidity and ventilation rate) produce designs with very different energy consumptions. Furthermore, the optimal ventilation rate (derived from a physics-based approach) was found to be far from values presented in guidance documents. Use of this new rate implies a 90% reduction in energy use, compared to the most conservative guidance, confirmed using measured data. This suggests this is a real issue and the existence of such contradictory guidance runs against the low carbon agenda.

Introduction

Buildings in use are responsible for approximately 40% of the total energy consumption in Europe [Eurostat (2008)]. Hence, there is a continuing emphasis in building design on reducing energy consumption and running costs. Unfortunately, there is a growing body of evidence suggesting that the known discrepancies between modelling and reality create a barrier to achieving low carbon buildings [Adeyeye (2007), Häkkinen (2011), Kershaw (2014), Osmani (2009), Zhu (2012)]. This paper examines if further conflicts in building services design guidance create further discrepancies, and if these are large enough to be considered detrimental to building energy performance.

Background

Design guidance and regulations can be seen as both drivers and barriers to low carbon design [Adeyeye (2007), Häkkinen (2011), Kershaw (2014), Osmani (2009), Zhu (2012)]. Williams and Dair (2007) showed that it is common for stakeholders' sustainability objectives to be restricted by regulation, and this could be attributed to policy and regulation lagging behind best practice. Despite this, Morton (2011) showed that the majority of activity related to low carbon design was to adhere to industry standards and guidance. The benefits stated by those surveyed by Morton were that guidelines provided clear standards, were effective, and made addressing environmental issues more routine (cheaper).

Williams and Dair (2007) also reported a lack of awareness of sustainability in general and a lack of experience in building sustainable developments amongst building professionals. This is echoed by Häkkinen and Belloni (2011) who found a gap in the knowledge of developers / clients regarding sustainable building and a lack of communication between building professionals. This lack of communication has been identified as a major barrier to achieving sustainable / low carbon design and prevents a design team from working effectively [Kershaw (2014)]. Williams and Dair (2007) state "*Without such information, those involved in development either as professional advisors or developers themselves are unlikely to take what they see as risks to achieve more sustainable outcomes.*" Morton (2011) suggests that while many individuals within an organisation may be open to changing practices and taking more risks, the power to do so rests with the more senior members of staff. In a survey of building professionals within a large international engineering firm it was found that the more senior an individual within an organisation the more resistant to change they were, and the more they believe that current practices were adequate. Other surveys of building professionals have reported similar findings [Adeyeye (2007), Osmani (2009), Zhu (2012)]. Exacerbating the resistance of building professionals to stray from traditional practices is a known overall lack of a stated sustainability requirement by clients [Osmani (2009)]. This is supported by the findings of Adeyeye (2007) who found that clients often do not even specify energy conservation requirements in design briefs.

A lack of communication between design team members and any gaps in knowledge will likely lead to individual design team members relying more heavily upon guidance documents. Therefore there is the need for guidance, policy and regulatory documents to be practical, accessible and up to date and not be in conflict. Adeyeye (2007) states "*User-specific documents such as a practical guide for clients, architects and engineers could also be useful*. …[as] *architects are more likely to consult simple, accessible and easy to use documents that offer practical information which can immediately be applied to design without the need for further interpretation or consultation.*"

In the typical architect-led design team, input from specialists can often occur late in the design process resulting in standard responses and typical off-the-shelf solutions [Kershaw (2014)]. Such highly standardised responses can fuel conflict with the architect, who will resist solutions that they view as an incomplete response to a bespoke project [Fischer (2009)]. If the architect does not understand the relevant principles, and the design team does not communicate effectively, then the building design process can become one of trial and error. It seems obvious then, that a clear set of guiding principles are required to influence industry to progress towards sustainable design principles [Adeyeye (2007), Kershaw (2014), Morton (2011), Zhu (2012)].

Swimming Pools

Swimming pool halls consume more energy per m^2 than almost any other building and often five times more per unit area than office blocks [Carbon Trust (2008)]. For swimming facilities a large part of the energy is used to maintain the temperature of the pool water and the temperature and humidity of the pool hall, changing rooms and other areas [Carbon Trust (2006, 2008), Passivpedia]. This is to overcome the cooling effect of water evaporation and maintain comfortable conditions for occupants. The processes of heating / cooling and humidifying / dehumidifying are typically energy intensive and hence care must be taken when sizing and commissioning these systems to avoid wastage. A study of a low energy German swimming pool [Passivpedia] showed that nearly half (47%) the heating energy used by swimming pool complexes is to ventilate and heat the pool hall (33%) and replace heat lost from the pool water due to transmission and evaporation (14%). The next largest values are heating replacement water for the swimming pool for sanitary reasons (33%) and heating of hot water for showers and basins (12%), heating of the changing rooms and other areas is minimal by comparison. The German study [Passsivpedia] indicated that typical swimming pools use on average ~3600 kWh/m^2 of pool area for space and water heating. This indicates that swimming pools are ideal candidates for the implementation of energy saving features and generation of renewable heat and energy.

The heating, ventilation and air-conditioning (HVAC) system is normally the primary (or only) means of controlling the pool hall air quality, temperature and humidity [Carbon Trust (2006 & 2008)]. The need for controlling temperature and humidity is two-fold. The presence of a large body of water within the pool hall leads to a high moisture content in the air above. This can lead to condensation on cold surfaces (such as windows and cold bridges) or in low airflow areas. Without the correct conditions this condensation can give rise to corrosion damage. The HVAC system also plays a key role in removing contaminants such as Chlorine from the air and producing comfortable environmental conditions for bathers, who would otherwise experience thermal discomfort due to reduced clothing levels and evaporative cooling from their skin.

Ventilating and heating pool halls can be rather complex and it is essential to manage these services correctly. The control of evaporation from the water surface is a function not normally encountered in standard HVAC systems, and therefore can be misunderstood by designers and engineers. While airflow is required to prevent condensation there is a direct link between the energy consumption of ventilation systems and evaporation of water from the pool, due to the increased air velocity over the water surface [Carrier (1918)]. The amount of heat in the pool lost to evaporation depends on the air conditions immediately above the pool (air temperature, humidity and velocity). This energy, together with a small amount of heat loss through conduction and radiation, represents a major part of the energy exchange from the pool water to the pool hall air. Controlling this is therefore the key to saving energy.

Given this complexity it is not surprising that guidance documents play a central role in swimming pool design. There are various industry guidelines in the UK relating to the environmental conditions and fresh air circulation within a pool hall. The guidance documents are generally in good agreement about the internal air temperature (~30 °C, a minimum of 1 °C above pool temperature) and relative humidity (60 % ± 10 %) (the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) guide suggests 50-60%) but are contradictory about ventilation rates. They hence point toward different ventilation solutions and the energy required to drive the system. This in turn has implications for the sizing of integrated renewable energy systems or the need for energy savings elsewhere in the building if the design is targeting a specific total energy demand (as is the case for example in Passivhaus design). The Sport England 'Swimming Pool Design Guidance Note' [Sport England (2011)] suggests an air change rate of 8 – 10 fresh air changes per hour (ac/h). This guidance seems misleading, as the actual fresh air exchange in litres per second needed to deal with condensation and other issues is not dependant on the volume of the pool hall, but rather the size of the pool surface and wet surround which are the source of evaporation. This will lead to increased energy usage for pool halls with higher ceilings, even if the water surface is the same size and hence has the same evaporation. In addition, since external air is typically cooler and drier than the internal air, if the fresh air change rate is too high this will lead to increased evaporation from the pool and increased heating and ventilation load and potentially humidification of the air to maintain occupant comfort.

By comparison, Good Practice Guide 219, 'Energy efficiency in swimming pools' [DETR (1997)] gives the following ventilation guidance at various points:

- 10 l/s per m^2 of total pool hall area
- 4 – 6 ac/h for standard use (8 – 10 for extensive water features i.e. flumes)
- Minimum 12 l/s per person
- 100% fresh (external) air operation should be available.

This guidance is also somewhat confusing since it implies several different ventilation rates and the final statement indicates that this might not be 100% fresh air and that some can be re-circulated, however, this is not stated explicitly. The general guideline of 10 l/s per m^2 of pool hall typically equates to the 4 – 6 ac/h for many pool halls [Carbon Trust (2008)], which implies an assumption about the height of the pool hall. The document CTV006 'Sports and Leisure – Introducing energy saving for business' [Carbon Trust (2006)] recommends 4 – 10 ac/h of fresh air coupled with variable speed fans to control humidity. No further details are provided and there is no mention of recirculation or that not all the air has to be fresh air. Alternative guidance from the Chartered Institution of Buildings Services Engineers (CIBSE) Guide B [CIBSE (2005)] references the good practice guide [DETR (1997)] for ventilation guidelines (section 2.3.21.7) but further states that the ventilation rate may be reduced with occupancy to save energy. In chapter 1, Guide B [CIBSE (2005)] states pool hall air temperatures of 23 – 26 °C in table 1.1 and a fresh air supply of 15 l/s of fresh air supply per m^2 of wet area in table 1.4. Later however, in chapter 2, Guide B [CIBSE (2005)] states temperatures of 27 – 31 °C (1K above water temperature) depending upon use and ventilation rates of 4 – 6 ac/h (8 – 10 ac/h for extensive water features) in table 2.27. In the surrounding text (section 2.3.21.7), airflow rates of 10 l/s per m^2 of total pool hall area and a minimum of 12 l/s per person of outside air. It also states that ventilation may be re-circulated to reduce fresh air supply to a minimum level of 30 %. The values presented in chapter 2 of Guide B [CIBSE (2005)] are generally in keeping with other guidance but it is concerning that the same document presents contradictory values.

The Carbon Trust in document CTG009 (2008) recommend similar levels again with ventilation of 10 l/s per m^2 of pool hall, which they state typically equates to 4 – 6 ac/h. However, here they recommend that the fresh air supply is supplied by variable speed fans and controlled with a dew point sensor or a relative humidity sensor and fresh air is supplied primarily to control humidity and prevent condensation. Other requirements for fresh air are met by default. No minimum for fresh air supply is stated. In document CTV006 the Carbon Trust (2006) states that where a full cover has been fitted ventilation can be switched off at night with no condensation issues.

Kalinina Anna summarised swimming pool ventilation guidance from several countries [Anna (2011)]: ASHRAE suggested fresh air supply values of 2.5 l/s per m^2 of wet area (pool + surround); the Finnish Building Code stated 2 l/s per m^2 of wet area; and the Russian Designing and Building Code provided a slightly different metric of 80 m^3/h per person (or 22.2 l/s per person). It can be seen from table 1 that for the pool hall considered later in this paper these values are largely comparable with 1 ac/h. It is important to note here that the majority of guidance seems to be linked to the area or either the pool surface, pool surface and wet area combined or the number of people, all of which are linked to the evaporation of pool water and hence the humidity levels within the pool hall (albeit in a complex way). From the guidance surveyed it appears that it is only the UK guidance that is linked to the volume of the pool hall and hence removed from the evaporation of the pool water. While CIBSE (2005) and the Carbon Trust (2008) also provide values of 10 l/s per m^2 of total pool hall area these values are at odds with other values presented in the guidance, it is also significantly higher than values provided by guidance for other countries.

This variation in UK guidance may have arisen as a result of confusion over the fresh air supply rate and overall ventilation rate (including recirculation). The former required to control humidity, temperature and air quality, the latter to prevent condensation. The climate within a swimming pool hall is generally mechanically controlled to provide comfort to swimmers and is therefore largely isolated from the external climate. This is confirmed by the similarity between the fresh air ventilation rates in the international guidance, despite variation in external climate.

The different fresh air ventilation rates expressed in different guidance documents will likely result in confusion and lead to energy wastage if an inappropriate value is chosen. It is known that when presented with contradictory or insufficient information clients and design teams will likely choose what is considered the safest option (highest ventilation rate) in order to mitigate potential risk. [Kershaw (2014), Williams (2007)].

Thermal Modelling of Swimming Pools.

Thermal modelling of buildings is an important tool that can be used to predict energy usage for compliance purposes, but can also be used as a design tool [Zhu (2012)]. A dynamic thermal modelling package is required to examine the interplay between weather, ventilation rates, various heat gains, internal environmental conditions and to assess how a building will perform under different representations of weather and climate. In order to achieve the goals of occupant comfort and minimal energy usage, accurate modelling is necessary to ensure optimal design [Kershaw (2014)]. There is however a problem when considering swimming pools, in that thermal models do not explicitly handle bodies of water and cannot estimate the latent and sensible plant loads. This means that either the team needs to pick a set of requirements directly from the design guidance, or engage in complex physics based calculations.

The modelling software used in this study is the Integrated Environmental Solutions: Virtual Environment [IES], as this is a common package in engineering practices. Although the approach detailed here could be applied to other thermal modelling software packages. To examine the implications of ignoring the guidance, but tackling the problem by a bottom-up calculation a new method for considering the energy balance within a pool was developed. This was based on calculating the rate of evaporation of water from the pool using the methodology outlined in the next section to give a latent heat gain in W/m^2, this latent gain is then applied to the pool hall in the model. The sum of the sensible heat loss and the latent heat loss from the pool will then approximate to the energy required to keep the pool water at the correct temperature. In addition we then need include the energy required to heat fresh water to replace the evaporated water.

Calculating Evaporation Rates

Compounding the issues with design guidance listed above, there is a lack of published information about the evaporation of water from pool surfaces. This makes it impossible for the heat loss, water demand or latent conditioning loads to be estimated easily. This means that design teams have little choice but to take the values presented to them at face value. There are however several different physics-based methods for estimating the evaporation from a pool surface in the literature, allowing for different values to be estimated depending upon what variables are known. Perhaps the best-known relationship is the Carrier equation [Carrier (1918)], which appears in the ASHRAE guides [ASHRAE (1987)]. When converted to metric units [Carrier (1918)] this equation is:

(1)
$$W_p = \frac{A(0.087 + 0.07815V)}{Y}\left[P_w - P_a\right]$$

where, W_p is the rate of evaporation (kg/s), A is the area of the pool (m^2), V is the air speed over the water surface (m/s), Y is the latent heat of water (kJ/kg), P_w is the saturation vapour pressure at the water surface temperature (kPa) and P_a is the saturation pressure at room dew point (kPa). Shah (2003) noted however that there is some discrepancy with the use of this equation within the ASHRAE guides over time, originally for unoccupied pools, but later used for pools with normal activity. This change of use may be a result of reports that the Carrier equation over estimates pool evaporation [Shah (2002)]. Utilisation factors are now sometimes used to modify the Carrier equation according to occupancy. This change in the ASHRAE guidance over time only further complicates the issue, as although the most recent guidance should be used, the phasing of different guidance documents means that older information may be stated and referenced.

There are many factors that will increase evaporation from a pool and these can be estimated and used to modify the rate of evaporation given for an unoccupied pool. Shah (2003) details four such factors: waves on the water surface, a wet-deck (i.e. water on the surrounding tiled area), the wet bodies of pool occupants and spray caused by activity. These can be used to adjust the rate of evaporation for an unoccupied pool E_0 to give an actual evaporation E by effectively increasing the total area over which evaporation can occur. Where,

(2) $$\frac{E}{E_0} = \frac{A_{pool} + A_{wetdeck} + A_{bodies} + A_{waves} + A_{spray}}{A_{pool}}$$

Thus the evaporation from an unoccupied pool is increased according to the ratio of the increased surface area (*A*) provided by waves, bodies, wet deck and spray to that of the pool. These areas can be estimated according to a pool utilisation factor F_u that is defined by:

(3) $$F_u = \frac{NA_{max}}{A_{pool}}$$

Where A_{max} is the pool area per person (including spray, waves, etc.) at maximum occupancy and *N* is the number of pool occupants. Biasin and Krumme (1974) showed A_{max} is almost constant at ~4.5 m^2 per person for ordinary swimming pools. Using this utilisation factor F_u the different areas can be estimated as:

(4) $$A_{wetdeck} = F_u A_{pool}$$

(5) $$A_{bodies} = 0.3 F_u A_{pool}$$

Smith (1993) estimated that the waves on the pool surface typically increase the surface area by ~20 %, with waves 150 mm high at 900 mm intervals. Thus,

(6) $$A_{waves} = 0.2 A_{pool}.$$

A_{spray} can typically be ignored under normal conditions and is only important in diving or sports pools [Shah (2003)]. These relationships are independent of pool occupancy and are only valid for $F_u > 0$. There are the potential problems with these relationships for higher levels of occupancy (greater F_u). The area around the pool is determined at the design stage, however the fraction of this surface that is wet, as a result of people getting in and out of the pool etc. ($A_{wetdeck}$) is determined by the occupancy level. As such $A_{wetdeck}$ can easily exceed available space if occupancy is high. For the pool considered later A_{pool} = 425 m^2 (for a 25 m × 17 m pool) but the total area of the pool hall is only 750 m^2. For the expected typical levels of occupancy (12m^2/person in the pool hall) we get an utilisation factor F_u = 0.66. Thus we can see that $A_{wetdeck}$ for typical occupancy is approaching the total available space. We could cap $A_{wetdeck}$ at 325 m^2, but this is still unrealistic as it is unlikely that all the space around the pool would be wet even if the pool were at maximum occupancy. Thus while these factors allow modification of an equation for the rate of evaporation from an unoccupied pool such as the Carrier equation there are limitations.

There are several relationships relating the evaporation from a pool to utilisation factor and environmental variables such as those proposed by Shah (2003, 2013), Biasin (1974) and Smith (1994, 1999). The work of Smith (1993, 1994, 1999) is widely referenced in the literature and if converted to metric units and written in the notation used above [Shah (2003)] gives the following relationship for evaporation (kg/m^{2}h):

$$E = \frac{(0.068 + 0.063F_u)}{Y} \Delta P \times 3600 \tag{7}$$

where E is the evaporation rate (kg/m^{2}h), F_u is the utilisation factor and ΔP is the difference (in kPa) between the saturated vapour pressure (P_w) at the water surface temperature and the partial vapour pressure at room temperature and humidity (P_r). P_w and P_r are given by:

$$P_w = 6.112e^{\left(\frac{17.67 \times T_w}{T_w + 243.5}\right)} \tag{8}$$

$$P_r = \frac{R_{hum}}{100} \times 6.122e^{\left(\frac{17.67 \times T_w}{T_r + 243.5}\right)}, \tag{9}$$

where R_{hum} is the relative humidity and T_w and T_r are the temperatures of the water surface and the room respectively. Note these equations produce pressures in mBar while ΔP is in kilopascals (kPa) (1 mBar = 100 Pa).

Smith's relationship [Smith (1994, 1999)] has been shown to produce a feasible rate of evaporation [Shah (2013)]. This relationship also has the benefit that it links evaporation rate to the utilisation factor accounting for use but doesn't require knowledge of the air speed over the water surface, which is hard to estimate at the design stage and is required to use the Carrier equation [Carrier (1918)]. Shah (2003, 2013) compared several relationships with different observations of evaporation and occupancy from the literature and found that the relationships of Smith (1994, 1999) performed well at typical occupancy levels ($F_u < 1$) but showed deviation at higher occupancies. Given the data presented by Shah (2003, 2013) we can conclude that the rate of evaporation given above is feasible, but also that several other relationships exist, however, for standard levels of occupancy there is little to distinguish between the work of Shah (2003, 2013), Smith (1994, 1999) or Baisin (1974). For these reasons this is the relationship that will be used in later sections, however the methodology presented in this paper does not discriminate between this and other methods of calculating the rate of evaporation.

Application

As stated earlier, this paper uses a live project to examine whether failings in design guidance can have a material effect on the low carbon agenda. The project chosen is a new Passivhaus [Passivhaus UK] pool to be located in Exeter, UK. Being Passivhaus, energy use needs to be kept to a minimum, and hence the choice of guidance document could be critical. The facility is to accommodate a 25m eight-lane main pool, a 13m-learner pool and a leisure pool with water features, changing and staff facilities, reception, restaurant/café and offices. In addition a dry sports facility with two dance studios, a fitness studio and adequate changing facilities is to be included. Figure 1 shows the dimensions of the main pool hall.

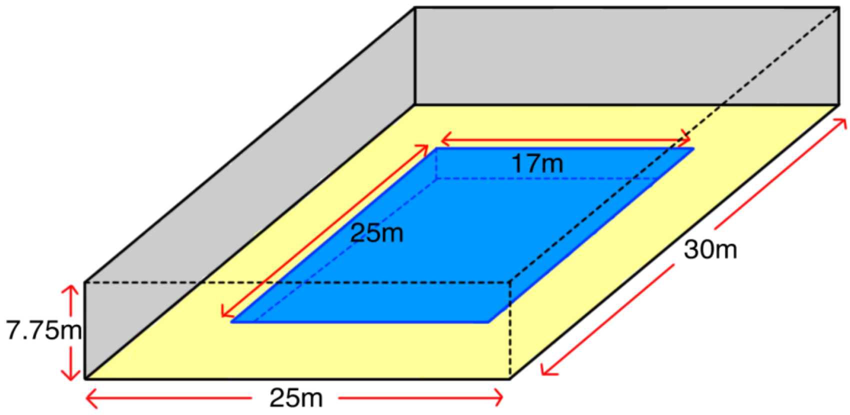

Figure 1 Illustration of the pool hall, showing representative dimensions.

Fresh air change rate (ac/h)	**Litres/second/m^2 pool hall**	**Litres/second/m^2 pool surface**	**Litres/second/person (F_u = 0.66)**
8	18.67	32.94	222.2
4	9.33	16.47	111.1
2	4.67	8.23	55.6
1	2.33	4.12	27.8
0.5	1.17	2.06	13.9
0.25	0.58	1.03	6.9

Table 1 Comparison of different metrics of volumetric airflow for the pool hall geometry used in this paper.

Based upon the expected levels of occupancy in the pool hall (63 people) the typical fresh air load would be 750 l/s (~0.4 ac/h) at 12 l/s/person fresh air. The only other Passivhaus pool in existence (the Lippe indoor pool in Lunen, Germany) employs an air change rate of 1.5 ac/h with 30% being fresh air. This compares to 4-5 air changes per hour, with approximately 10-30% being fresh air for other modern swimming pools using recirculatory ventilation systems [Passivpedia]. It seems then that ~0.5 ac/h of fresh air is considered acceptable for controlling air quality, with sufficient air velocity provided by recirculation to prevent condensation. The Sport England 'Swimming Pool Design Guidance Note' [Sport England (2011)] suggests an air change rate of 8 – 10 fresh air changes per hour (ac/h). This equates to a fresh air load of 17,500 l/s for the proposed design (the volume of the pool hall is 6300 m^3 including rooflight wells) and a predicted space-conditioning load (sensible and latent at 10 ac/h) for the main pool hall of ~3500 MWh over the year (calculated by IES using the methodology outline in the next section). Taken together this gives us a range of values for analysis covering the full gambit of guidance (Table 1).

Calculations
Table 2 shows the maximum pool water temperatures as stipulated by the Pool Water Treatment Advisory Group (PWTAG) [Sport England (2011)]. These are maximum temperatures and pool operators may run temperatures 1-2 °C lower to save energy.

Recommended maximum pool water temperatures	**PWTAG 1999**	**PWTAG 2009**
Competitive swimming / diving / fitness	27 °C	28 °C

Recreational, adult pool	28 °C	29 °C
Leisure pools	29 °C	30 °C
Children's swimming	29 °C	31 °C
Babies, young children, disabled	30 °C	32 °C

Table 2 Maximum pool temperatures adapted from Sport England Guidance (2011).

If we assume that the main pool (425m^2) is operated at 28 °C to give a good mix between comfort and energy saving, then according to the above guidance the pool hall air temperature would be 29 °C (typically 1°C above water temperature) with a relative humidity (R_{hum}) of between 50% and 70% [Sport England (2011), DETR (1997)]. This gives values for P_w, P_r and ΔP of:

P_w = 3.779 kPa
$P_r = R_{hum}/100 \times 4.007$ kPa
$\therefore$ 0.974 kPa $\leq \Delta P \leq$ 1.776 kPa (for 70% $\geq R_{hum} \geq$ 50%).

The latent heat of vaporisation for water is 2260 kJ/ kg, thus, for an average utilisation factor F_u = 0.66 during occupied hours the rate of evaporation given by Smith's relationship (1999) per m^2 of pool area is:

E = 0.309 kg/m^{2}h or a latent heat loss of 194 W/m^2 (for 50% R_{hum});
E = 0.240 kg/m^{2}h or a latent heat loss of 150 W/m^2 (for 60% R_{hum});
E = 0.170 kg/m^{2}h or a latent heat loss of 106 W/m^2 (for 70% R_{hum}).

As expected the rate of evaporation from the water surface varies with relative humidity, this has to be balanced with the energy required to heat incoming air. If we know the evaporative heat loss from the pool we can estimate the total heating energy requirements for the pool. The above values are both the heating energy required to maintain pool temperature and also the latent gain into the pool hall.

To implement this methodology with the dynamic thermal model, we need to create the geometry and profiles to account for the latent and sensible heat gains. To account for the sensible heat gain we represent the body of water as a room beneath the pool hall maintained at a constant temperature, with the adjoining ceiling (the surface of the water) represented as a window with transmittance = 1, absorbance = 0, reflectance = 0, refractive index = 1 and IR emissivity = 1 (water is almost a perfect black body at these temperatures). This combination of values will allow sensible radiation emitted to pass from the pool to the pool hall unimpeded, this method is based upon that suggested by IES for the inclusion of bodies of water. In order to ensure that the window representing the surface of the water is at the correct temperature, the construction needs to be thin (minimum in IES is 1mm) and have a low surface resistance (a value of 0.01 m^{2}W/K was used in this study). This will allow the upward facing surface of the window representing the surface of the pool water to reach the correct temperature, thus allowing the sensible gains from the body of water to be included. The low surface resistance value is applied to the internal (downward facing) surface of the glass only, while emissivities are altered for both surfaces of the glazing representing the water surface. Evaporation from the pool surface was estimated using formulae for the evaporation of water as detailed previously and incorporated into the pool hall as a latent heat gain. In addition air exchange including infiltration was turned off between the pool zone and the pool hall. This means that heat can only be transferred from the pool either by conduction through the pool walls (to the earth) or by radiation or convection into the pool hall above. A limitation of this method is that the thermal inertia of the water cannot be included as there is no material that represents water within the software. While a limiting factor the similar but lower temperature of the water compared to the air and the humidity in the pool hall means that the net sensible heat transfer will be minimised and it can be assumed that discrepancies due to an incorrect thermal inertia will also be small if the pool basin is well insulated. The geometry of the pool can be seen in figure 2, the walls and floor have U-values of 0.35 W/m^{2}K and 0.25 W/m^{2}K respectively.

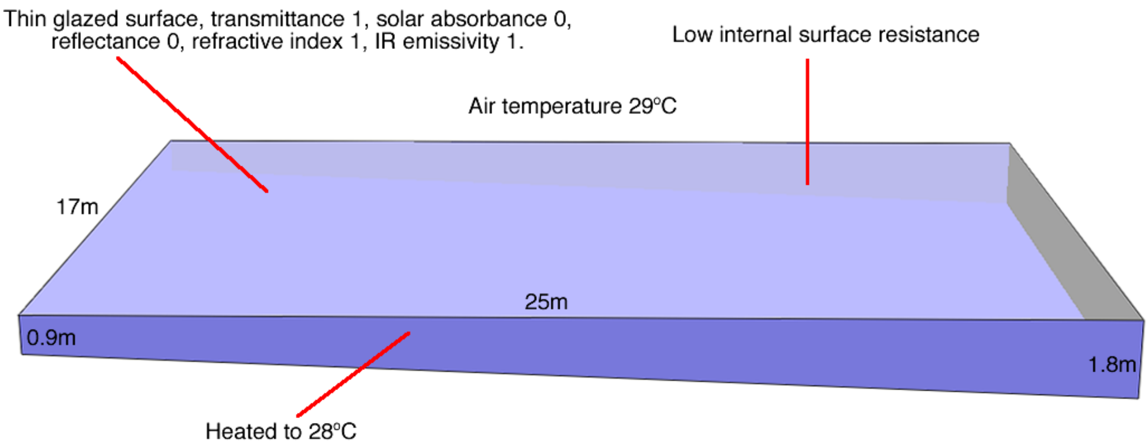

Figure 2 Illustration of the room representing the pool and relative values.

The room representing the pool is heated to 28°C continuously and has no other internal gains and no air exchanges with the outside or other spaces. A domestic hot water load was added to the pool to account for the energy required to heat replacement water for that lost by evaporation. This equated to hot water requirements of 131.33 l/h, 102 l/h and 72.25 l/h for R_{hum} = 50%, 60% and 70% respectively, the water supply temperature was 10°C and the water was heated to 28°C. A latent heat gain in W/m^2 was added to the pool hall corresponding to rate of evaporation from the pool, this was adjusted from the values shown above to account for the fact that the pool hall has a larger area than the pool. The room is heated to 29°C, with cooling occurring at 32°C, the humidity set to 50%, 60% or 70%, corresponding to which rate of evaporation is used. Both the pool hall air temperature set point and the latent heat gain are controlled with a modulating profile linked to occupancy—this follows from the assumption that a tight fitting cover will be used on the pool outside hours to save energy.

There is the common perception that swimming pools require dehumidification due to the evaporation from the pool water surface. However, high rates of fresh air changes per hour can lead to humidification being required to maintain environmental conditions within the pool hall. This is especially true in the winter months when the moisture content of the outside air is lower. To explore the effect of different levels of relative humidity and fresh air change rates on the energy consumption of the pool complex, humidity levels were controlled in the ranges of 50-60%, 55-65% and 60-70% and the air change rate varied. These levels were chosen to represent each of the evaporation rates calculated at R_{hum} = 50%, 60% and 70% respectively. The ranges were set so that the relative humidity did not move outside of the range set in guidance without resorting to excessive control [CIBSE (2005), DETR (1997), Sport England (2011)]. Energy used to heat replacement water attributed to pool water evaporation was calculated at 13.3 MWh, 10.3 MWh and 7.3 MWh per annum for the three humidity ranges (in increasing order). To minimise energy usage it is generally advisable to have as wide a deadband as possible between control set points while still maintaining comfort, so a fourth range of R_{hum} = 60% ±10% was also investigated. In this case the latent gain in the pool hall from pool evaporation was varied with the relative humidity in the pool hall. Pool water refresh rate and the energy required to heat that water has not been included here, however, this could be accounted for by simply increasing the domestic hot water supply in the model and would be the same in each case.

Including a latent gain equivalent to the evaporation from the pool water surface into the pool hall allows the use of dynamic thermal modelling software to account for all the loads attributed to running a swimming pool. The domestic hot water load represents the heating of replacement water, the sensible heat load for the pool accounts for heat loss via conduction and radiation, the latent gain into the pool hall is equivalent to the evaporative cooling load on the pool water and hence the heating load required to maintain the pool temperature.

Results

Dynamic thermal simulations were performed as described above using a Test Reference Year (TRY) type weather file for Exeter [Eames (2011)]. (A TRY is a representation of the typical climate for a location.) We found that at higher fresh air supply rates, moisture and relative humidity are at the lower limit of the allowable range while at lower fresh air supply rates values are at the higher limit, during occupied hours. This implies a change in operation of the pool hall from one of humidification at high fresh air supplies to one of dehumidification at lower fresh air supplies. This is not unexpected but it does provide insight into how a pool complex can be made more efficient. Ideally we want to identify the fresh air supply rate that will require the least amount of energy to be expended to maintain comfort and control condensation.

	8 ac/h	**4 ac/h**	**2 ac/h**	**1 ac/h**	**0.5 ac/h**	**0.25 ac/h**
50-60% R_{hum}	1020 / 0.64	428 / 0.58	139 / 1.5	17 / 12	0.6 / 61	0.4 / 112
55-65% R_{hum}	1314 / 0.09	593 / 0.15	234 / 0.24	62 / 1.3	3.1 / 16	1.1 / 64
60-70% R_{hum}	1612 / 0	762 / 0	338 / 0.02	126 / 0.11	27 / 1.2	2.3 / 17
50-70% R_{hum}	1019 / 0	428 / 0	139 / 0.01	17 / 0.01	0.6 / 0.01	0.2 / 1.1

Table 3 Annual humidification / dehumidification energy consumption in MWh for the pool hall at different fresh air supply rates and ranges of relative humidity.

For simplicity here we have assumed that the pool cover is perfectly fitting and that there is no evaporation overnight [Carbon Trust (2008)]. It is also worth noting here that we are not showing the fan energy required, this is because this should be the same in all cases as air circulation is required to control condensation. The analyses are concerned with the fraction that is external fresh air as apposed to recirculated air. The energy required to heat water to replace the evaporation varies with the relative humidity level above the pool. This was calculated to be 7.3 MWh, 10.3 MWh and 13.3 MWh over the year respectively for the relative humidity ranges 50-60%, 55-65% and 60-70%. The simulation does not allow the domestic hot water load to be varied dependant on the relative humidity unlike sensible and latent loads. Instead steady state values were calculated and the 50-70% range was allocated the same value as 55-65% relative humidity range.

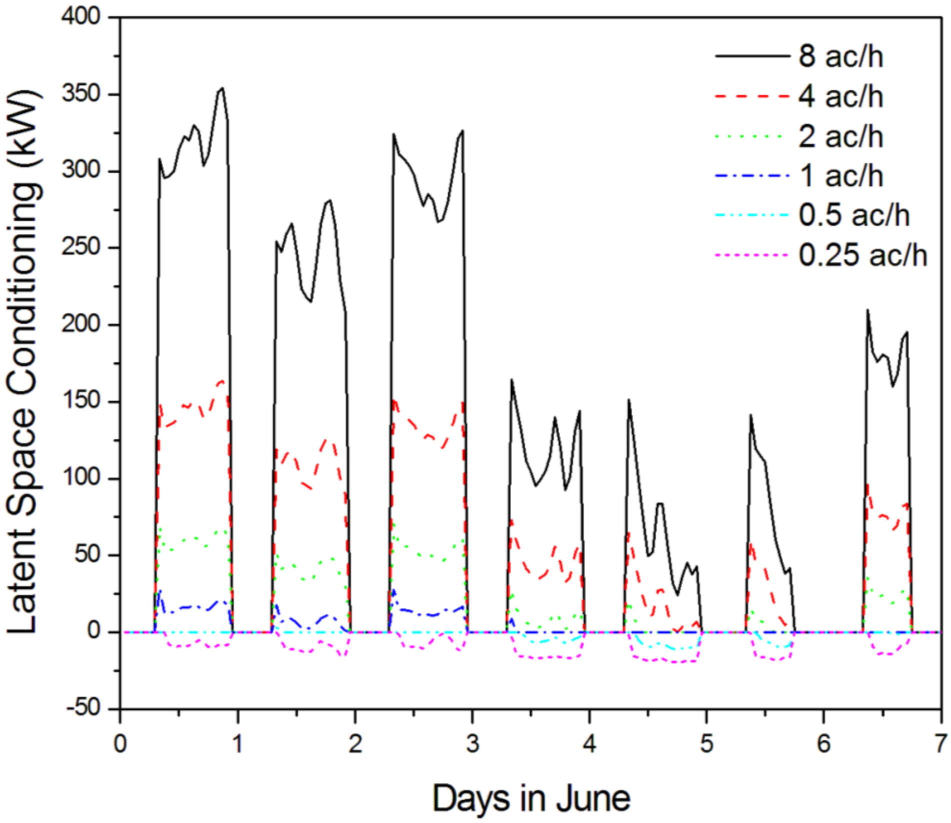

Figure 3 Plot of latent space conditioning for the pool hall. For clarity data is only shown for a single week in June at different fresh air supply rates with R_{hum} controlled to 60% ±5%. Positive values indicate humidification while negative values are dehumidification.

We can see from figure 3 and table 2 that as the fresh air supply is decreased we move from a situation of humidifying the internal spaces to one of dehumidifying. This rises from the fact that the outside air is typically cooler and has lower moisture content than the pool hall and that there is a latent gain from the evaporation of water from the pool surface. This is further exacerbated by the fact that the outside air is typically cooler and hence higher fresh air change rates will lead to an increase in the heating load for the pool hall. Figure 4 shows the sensible and latent loads for the pool hall for different fresh air change rates and ranges of relative humidity control.

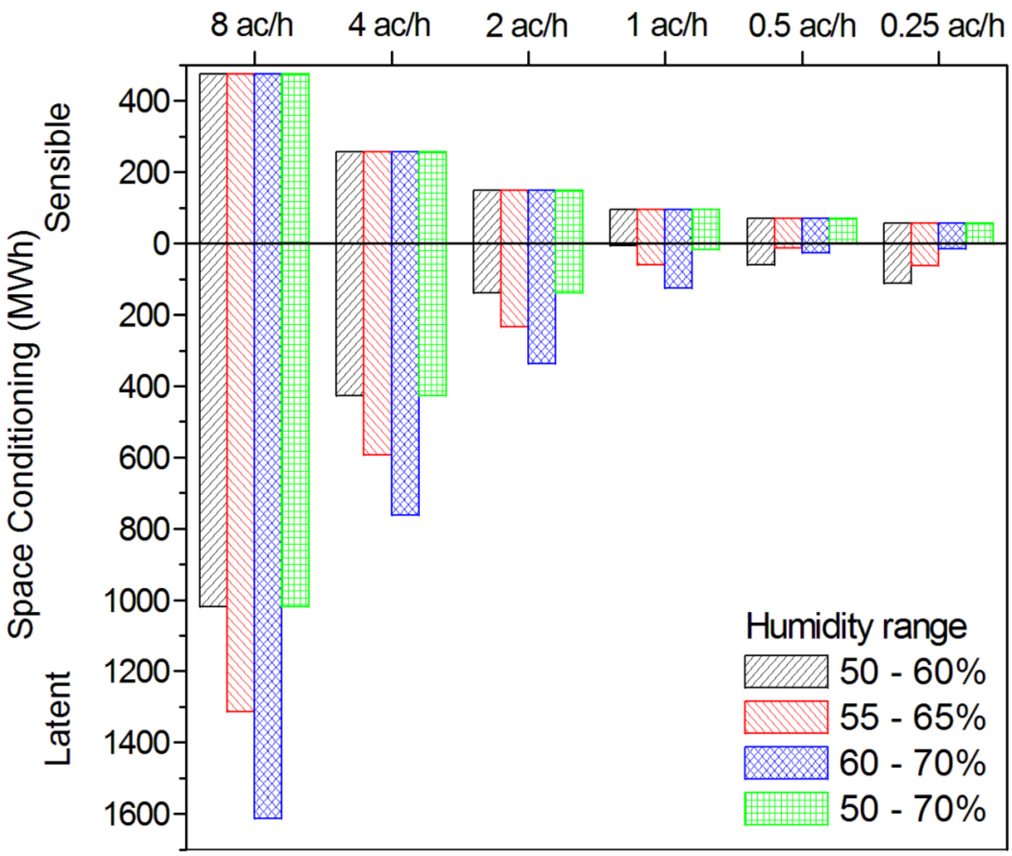

Figure 4 Comparison of sensible (above 0 line) and latent (below 0 line) loads for different fresh air change rates and relative humidity ranges.

In theory by controlling the rate of fresh air supply for the pool hall it should be possible to design a swimming pool that does not require either humidification or dehumidification. However, in practice it is likely that some dehumidification will still be needed. The key is to minimise these loads as much as possible to minimise energy usage. We can see from figure 4 that the wider humidity range results in reduced environmental conditioning loads. The 0.5 ac/h of fresh air results in the lowest latent loads however, the 0.25 ac/h of fresh air results in the lowest sensible loads, with 0.25 ac/h using the lowest total amount of energy for the typical Exeter climate.

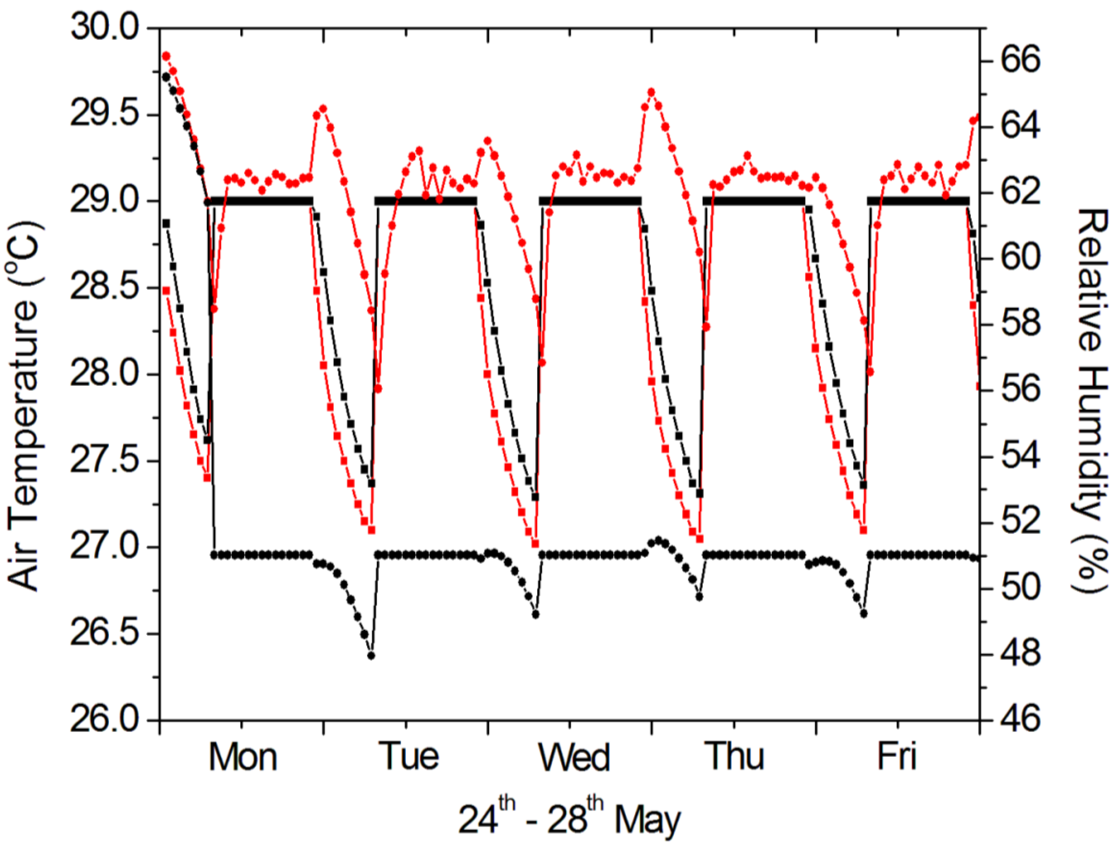

Figure 5 Plot of air temperature (squares) and relative humidity (circles) within the pool hall for typical weekday operation. Data shown for 8 ac/h (black line) and 0.5 ac/h (red line) of fresh air with relative humidity confined between 50%-70%.

The simulation results show that the key energy loads for the building can be significantly reduced from the levels indicated by the guidance documents, and the humidification and dehumidification loads can be reduced almost to zero. Figure 5 shows that the operation of the pool hall during occupied hours maintains air temperatures at 29°C and the relative humidity within the accepted bounds required to provide thermal comfort. The figure shows that the lower fresh air change rate (red line/circles) produces a relative humidity that is able to vary naturally within the confined bounds while the higher fresh air change rate (black line/circles) produces a relative humidity that is close to the lower bounds.

Evaluation

While the simulations presented here cannot be validated against the building until it is constructed and monitored for at least a year, we are able to compare the findings to data collected from a similar swimming pool complex in Lunen (Germany) [Passivpedia]. The Lunen pool was also designed to Passivhaus standards and was subject to extensive monitoring (between March 2012 and March 2013) as well as in-use optimisation of ventilation and humidity control. This in-use optimisation found that optimal running conditions for the pool halls were a ventilation rate of 4 l/s per m^2 of pool surface area (equivalent to ~1 ac/h for the Exeter pool see table 1) with ~30% being external fresh air, the rest recirculated. There were no humidification or dehumidification loads with relative humidity controlled purely by fresh air ventilation rate and the optimal level of relative humidity in the pool hall was found to be 64%, balancing condensation control against comfort and pool evaporation. The corresponding sensible heat loads for the main pool hall also were found to be in good agreement with our results (159 kWh/m^2 per annum, versus the 163 kWh/m^2 per annum found for 0.5ac/h of fresh air in this study). These findings from the Lunen pool confirm our calculations and show that if the UK design guidance were ignored in favour of a physics-based calculation, it is possible to significantly reduce the sensible and latent loads of a pool complex.

Discussion

In this paper we have examined the effect of varying guidance on design requirements. We have shown that not only are there inconsistencies between guidance documents but also within the same guidance document. By applying this guidance to a live project we have further shown that these differences can be considerable. In the case of the swimming pool hall chosen, the simulations presented here show that the sensible and latent conditioning loads can be reduced to only ~4% of that expected if the most aggressive guidance (that of Sport England) was followed to the letter, i.e. with 8 ac/h of fresh air being supplied to the pool hall. This case study points to a considerable disconnect between the guidance and the low carbon agenda.

In order to avoid confusion, guidance needs to be clear, concise and transparent. For the swimming pool example the difference between fresh air and recirculation should be stated explicitly, and the fresh air change rate should be linked to the source of the latent gain (evaporation), i.e. the pool surface or the wet area around the pool and air supply rate should be in litres per second per unit area, not air changes per hour to avoid variation with height of pool hall. Additionally, the volume of fresh air required to control pollutants such as CO_2 and Chlorine should be stated for clarity and to mitigate client fears over reducing fresh air change rates. Since the lowest energy consumption occurs at different fresh air supply rates for different relative humidities we can assume that the Carbon Trust (2008) recommendation to use variable speed fans to deliver fresh air dependant upon either a dew point or relative humidity sensor will reduce energy usage yet further. Internal relative humidity will be dependant upon the external temperature and humidity and therefore the amount of fresh air required will also vary in order to control humidity levels in the pool hall, avoid condensation and provide thermal comfort to occupants. Implementation of variable speed fans or dampers to control fresh air supply while maintaining air circulation velocity within the pool hall to control condensation will likely lead to considerable energy savings over supplying only external fresh air as per guidance.

For project like swimming pools, which are complex and infrequent projects for design teams, guidance is extremely important, providing information on building operation and highlighting best practice. The conservative nature of clients and design teams, will likely mean that the most aggressive guidance is chosen and is followed explicitly. Therefore, ambiguity and discrepancies between guidance will only lead to confusion and buildings that are inefficient and potentially uncomfortable.

In general, design guidance and regulations are known to be both drivers and barriers to low carbon design [Adeyeye (2007), Häkkinen (2011), Kershaw (2014), Osmani (2009), Zhu (2012)]. Morton (2011) showed that the primary activity of design teams embarking on low carbon design projects was to adhere to industry guidance and best practice documents. The engineer’s view that guidelines provide standard responses and make the design process and build cheaper is perhaps in conflict with architects resistance to standard solutions for bespoke projects [Fischer (2009)]. We can surmise therefore, that guidance needs to be clear, concise and use consistent units. Additionally, guidance should fulfil the roles of providing accessible information to designers/engineers and illustrating best practice, but also allow enough freedom for designers to incorporate energy efficient features or new technologies in the face of conservative clients and design team members who are unwilling to take risks in an attempt to achieve more sustainable outcomes [Williams (2007)].

Summary

In order to handle complex situations in a cost effective manner, design teams rely a multitude of design guidance. Given anecdotal evidence that often this guidance is conflicting or contradictory, concerns exist that design teams will opt for whichever is viewed as the most conservative or aggressive. This has the potential to lead to unnecessary energy use and be in direct conflict with the low carbon agenda. To quantify the impact, and to discover if this is a genuine concern, we investigated the impact on energy use of using the full range of design standards for commercial swimming pool halls. Two things were found. Firstly, the different standards (which revolve around temperature, humidity and ventilation rate) give rise to designs with very different energy consumptions. Secondly, the optimum ventilation rate (arrived at via a bottom up, physics based, approach) was far from the values presented in guidance and best practice documents. Using this value allowed a >90% reduction in pool hall energy consumption. This suggests that, at least in this case, it is indeed true that industry-standard environmental design guidance can lead to large differences in final design energy usage, the modeling suggests that this could have a considerable impact on energy use and resultant carbon emissions, and that, although cost effective in terms of design time, relying on off-the-shelf guidance, rather than bespoke calculation, can go against the low carbon agenda of the client.

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